

AN ~ 4.35 Ga Ar-Ar AGE FOR GRA 8 AND THE COMPLEX CHRONOLOGY OF ITS PARENT BODY.

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Introduction: GRA06128 and GRA06129 (hereafter GRA 8 and GRA 9) are partial melts of a parent body of approximately chondritic composition [1-3]. We [4,5] reported a conventional ¹⁴⁷Sm-¹⁴³Nd isochron age of 4.559±0.096 Ga and a ¹⁴⁶Sm-¹⁴²Nd model age of 4.549±0.036 for combined data for the two rocks. Plagioclase plus whole rock and leachate (~phosphate) samples gave a secondary ¹⁴⁷Sm-¹⁴³Nd age of 3.4±0.4 Ga [5]. An ³⁹Ar-⁴⁰Ar age of 4.460±0.028 Ga [3,6] was interpreted by [3] as dating metamorphism in GRA 9. We report ³⁹Ar-⁴⁰Ar ages in the range ~4344-4366 Ma for GRA 8, establishing similar but different ³⁹Ar-⁴⁰Ar ages for the two rocks, consistent with their different Sr-isotopic systematics [5], and discuss these ages in the context of the complex sequence of events that affected these samples (*cf.* [3]).

³⁹Ar-⁴⁰Ar Stepped Ar-Release Ages for GRA 8:

We did a stepped-temperature Ar extraction (49 steps) of a plagioclase separate of GRA 8 (12.7 mg) of low magnetic susceptibility (Fig. 1). Small age variations occurred among “phases” with different K/Ca at low, intermediate, and high extraction temperatures, and the summed age is 4354 Ma. Partitioned according to the fraction of ³⁹Ar released, the calculated ages varied from 4326±18 to 4344±14 to 4362±18 Ma (1σ) for 4-14%, 14-47%, and 52-96% ³⁹Ar released, resp. A single temperature step for 47-52% of the ³⁹Ar release appeared to mark a transition in the gas release mechanism as also seen in an Arrhenius plot constructed from the data (Fig. 2).

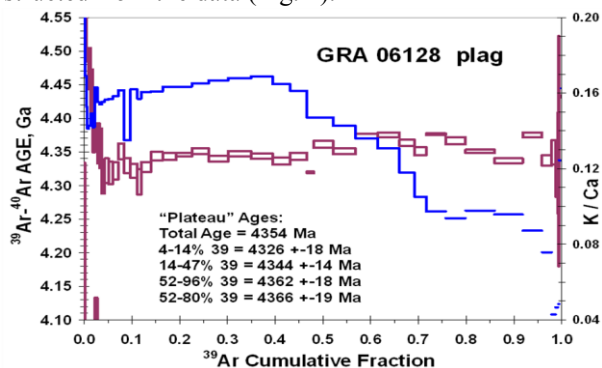


Figure 1. Calculated ³⁹Ar-⁴⁰Ar ages as a function of the cumulative fraction of ³⁹Ar released.

Arrhenius Plot for Stepped Ar-Release: In Fig. 2 values of the diffusion parameter D/a^2 calculated for each temperature interval up to 940°C (gray circles) are plotted vs. reciprocal absolute temperature (T)

expressed as 1000/T. Two diffusion regimes can be mathematically decoupled as shown by the two straight lines with the shallowest and steepest slopes (also see Fig. 1). An abrupt transition in degassing occurs at 1000/T ~0.82 (T=940°C), and the diffusion rate and activation energy decrease. Although the K/Ca ratio lies near K/Ca =0.13 reported for plagioclase by EMPA [3], a change in K/Ca also begins near the 940°C transition. We interpret this transition as due to a structural change in the K-bearing phases. We suggest this change was either induced by the laboratory heating or is relict from sub-solidus reequilibration on the parent body.

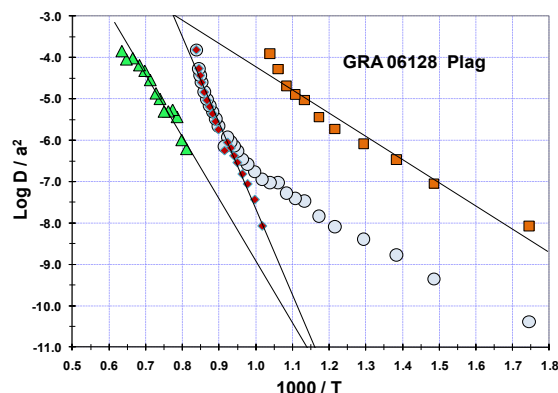


Figure 2. Arrhenius diffusion plot of log D/a^2 vs. reciprocal temperature (in K) for ³⁹Ar release from GRA 8.

Discussion: Viewed in isolation, these ³⁹Ar-⁴⁰Ar data are well-defined and could be interpreted as giving a relatively unambiguous chronology for GRA 8 consisting of initial formation at 4366±19 Ma (“most reliable” high-T age for 52-80% ³⁹Ar release) followed by final closure to Ar loss at 4344±14 or 4326±18 Ma as a result of subsolidus recrystallization (*cf.* [3]). However, consideration of all the chronological data for GRA 8/9 presents a more complicated picture.

Comparison to ³⁹Ar-⁴⁰Ar age of GRA 9. Fernandes [3,6] reports the ³⁹Ar-⁴⁰Ar age of GRA 9 to be 4460±28 Ma. Thus, the ³⁹Ar-⁴⁰Ar ages of GRA 8 and 9 appear to be clearly resolved, which we suggest is the result of different thermal histories for the two samples.

Comparison to ¹⁴⁷Sm-¹⁴³Nd isochron ages. The ¹⁴⁷Sm-¹⁴³Nd data for GRA 8 and 9 are complex (Fig. 3). With the assumption that both bulk rocks remained closed isotopic systems, the data appear to show a secondary age of 3.4±0.4 Ga for plagioclase/whole rock superimposed on a primary age of 4559±96 Ma

for pyroxene/whole rock [5]. However, if the isotopic system were *open* due, e.g., to the introduction into a mainly plagioclase/pyroxene cumulate rock of a phase from which phosphate crystallization occurred, the necessity to include the “whole rock” (WR) data in a primary isochron fit would be removed. In this case, a plagioclase plus pyroxene tie-line gives an apparent age of 4.24 ± 0.07 Ga (2σ), nearly within error limits of the intermediate-temperature ^{39}Ar - ^{40}Ar age of 4344 ± 28 (2σ). However, a similar exercise for GRA 9 results in an apparent age of 4.00 ± 0.11 Ga. This age is younger than the ^{39}Ar - ^{40}Ar age, but the first $\sim 11\%$ of the gas release gives a hint of a younger age near ~ 4.0 Ga [6].

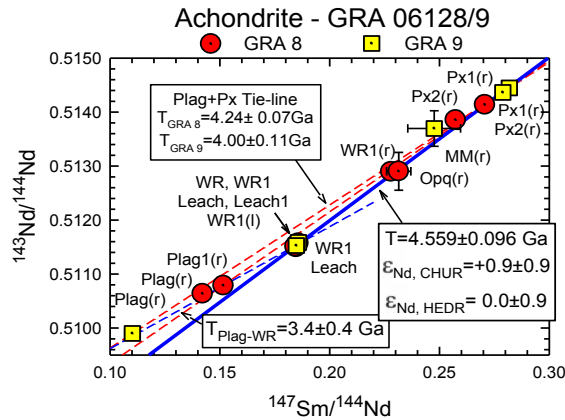


Figure 3. ^{147}Sm - ^{143}Nd data for GRA 8 and 9 [5]. Pyroxene-plagioclase tie-lines have been added to show the effect of the leachate (\sim phosphate data).

Comparison to ^{87}Rb - ^{86}Sr data. The ^{87}Rb - ^{86}Sr isochron ages are relatively poorly defined because of terrestrial contamination and the modest range in $^{87}\text{Rb}/^{86}\text{Sr}$ ratio [5]. Fig. 4 shows the Rb-Sr data in a (T, I_{Sr}) plot for those data judged to be most reliable. The ^{39}Ar - ^{40}Ar ages for GRA 8 and GRA 9 are plotted within the error parallelograms for the Rb-Sr data. The two data sets are consistent in showing that (a) GRA 8 and 9 differ, and (b) the ^{39}Ar - ^{40}Ar ages are close to the nominal ages obtained from the Rb-Sr isochrons. We noted previously that evolution from $(^{87}\text{Sr}/^{86}\text{Sr})_i \sim 0.698934$ for CAI at typical chondritic $^{87}\text{Rb}/^{86}\text{Sr}$ (μ) ~ 0.82 would require ~ 15 Ma for GRA 9 and ~ 40 Ma for GRA 8, resp. [5]. With the same assumptions, but treating the ^{39}Ar - ^{40}Ar ages as crystallization ages requires a precursor with lower $^{87}\text{Rb}/^{86}\text{Sr} \sim 0.24$ like that in CV chondrites. Interestingly, Arai et al. [7] suggested a volatile-rich carbonaceous chondrite parent asteroid for GRA 01628/9.

Alternative scenarios. Shearer et al. [3] recognize three major post magmatic events: (1) subsolidus re-equilibration to form a granoblastic texture; (2) reaction between the primary magmatic phases and either

a residual melt or a fluid phase; (3) low temperature alteration along grain boundaries and fractures. They equate the ~ 4.46 Ga ^{39}Ar - ^{40}Ar age of GRA 9 [3,6] to (1) above. Because ^{40}Ar would be rapidly outgassed at the corresponding temperatures, we equate subsolidus equilibration to the 4344 ± 14 Ma age obtained for GRA 8 at intermediate temperatures. We furthermore equate the younger 3.4 ± 0.4 Ma secondary Sm-Nd isochron to process (2) above. Low temperature alteration probably is manifested only as “isotopic disturbances”. Two alternatives for the primary crystallization ages of GRA 8 and 9 are: (1) Both formed ~ 4.56 Ga ago, and ^{39}Ar - ^{40}Ar ages between ~ 4.56 Ga and ~ 4.34 Ga ago are due to slow cooling of the parent body or separate impact events. (2) The crystallization age of each stone may be close to its ^{39}Ar - ^{40}Ar age, i.e., for GRA 8 the high temperature age of 4362 ± 18 Ma. This interpretation implies late magmatism on the parent body, and allows easy interpretation of the Rb-Sr data, but requires the ~ 4.56 Ga ages to have been carried into the rocks via phosphates introduced via open system reactions with external melts or fluids. Shearer et al. [3] identify merrillite as one of the primary magmatic phases favoring (1) above, but Treiman et al. [1] note phosphate replacing pyroxene and merrillite replacing apatite, perhaps a hint of open system processes permitting (2) above.

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Achondrite GRA 06128/9, Meteorites & Silicate Inclusions in Iron Meteorites IAB

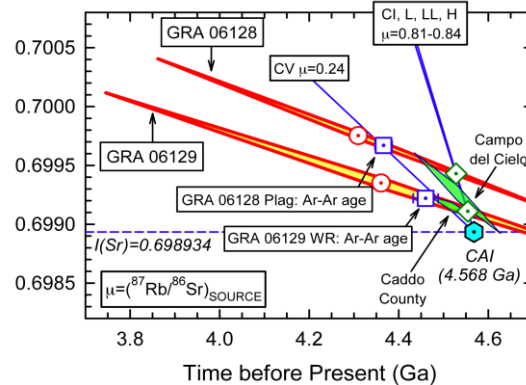


Figure 4. (T, I_{Sr}) for GRA 8 and 9 showing the location of the ^{39}Ar - ^{40}Ar ages of these samples within the corresponding error parallelograms. Updated from [5].

References: [1] Treiman A. H. et al. (2008) LPS XXXIX, Abstract #2214. [2] Day J. M. D. et al. (2009) *Nature*, 457, 179-182 [3] Shearer C. K. et al. (2009) *GCA*, doi:10.1016/j.gca.2009.10.029. [4] Nyquist L. E. et al. (2008) *Meteoritics & Planet. Sci.*, 43, A119. [5] Nyquist L. E. et al. (2009) LPS XXXX, Abstract #1290. [6] Fernandes V. A. and Shearer C. K. (2010), this meeting. [7] Arai T. et al. (2008) LPS XXXIX, Abstract #2465.

An ~ 4.35 Ga Ar-Ar Age for GRA 8 and the Complex Chronology of its Parent Body



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Introduction

- Achondrite, GRA 06128/9 partial melts of a parent body with chondritic composition (Treiman et al., 2008; Day et al., 2009; Shearer et al., 2010)
- ^{147}Sm - ^{143}Nd age of 4.559 ± 0.096 Ga for GRA 8/9, ^{146}Sm - ^{142}Nd age of 4.549 ± 0.036 Ga (Nyquist et al., 2008; Nyquist et al., 2009)
- Secondary ^{147}Sm - ^{143}Nd age of 3.4 ± 0.4 Ga in Plagioclase & Whole rock (Phosphate) (Nyquist et al., 2008)
- ^{207}Pb - ^{206}Pb age of 4.517 ± 0.060 Ga in chlorapatite for GRA 8/9 (Day et al., 2009)
- ^{26}Al - ^{26}Mg age of 4.561 Ga for GRA 9 (Shearer et al., 2010)
- ^{39}Ar - ^{40}Ar age of 4.460 ± 0.028 Ga for GRA 9 (Shearer et al., 2010, Fernandes and Shearer, this conference)
- K-Ar age = 4.3- 4.5 Ga (Matsuda et al., 2008)
- Cosmic-Ray Exposure age= 3 Ma (Matsuda et al., 2008)

Ar-Ar Age for GRA 8 plag

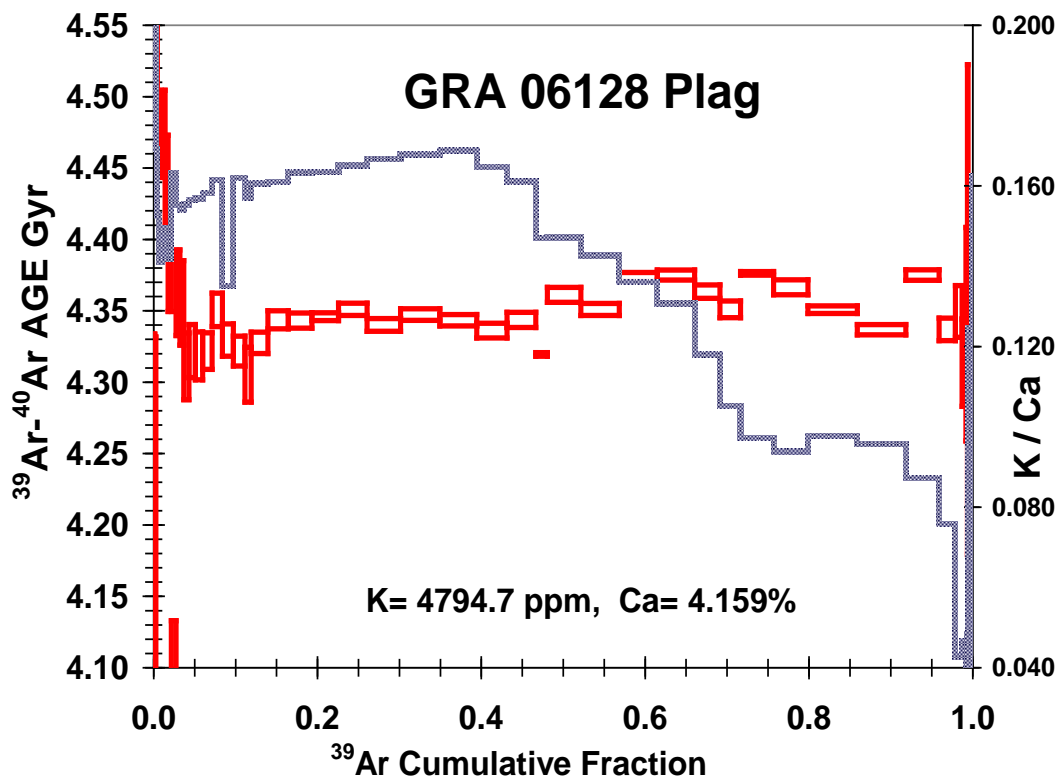
GRA 06128 Plagioclase Separate (12.7 mg by low magnetic susceptibility, 100-200 mesh), 49 heating steps over 300-1600°C.



Calculated ages are: ➤ 4.349 Ga (1.4-99% of ^{39}Ar release);

Ages suggest slight upward slope. ➤ 4.326 ± 0.018 Ga (4-14% of ^{39}Ar release)

➤ 4.362 ± 0.018 Ga (52-96% of ^{39}Ar release).

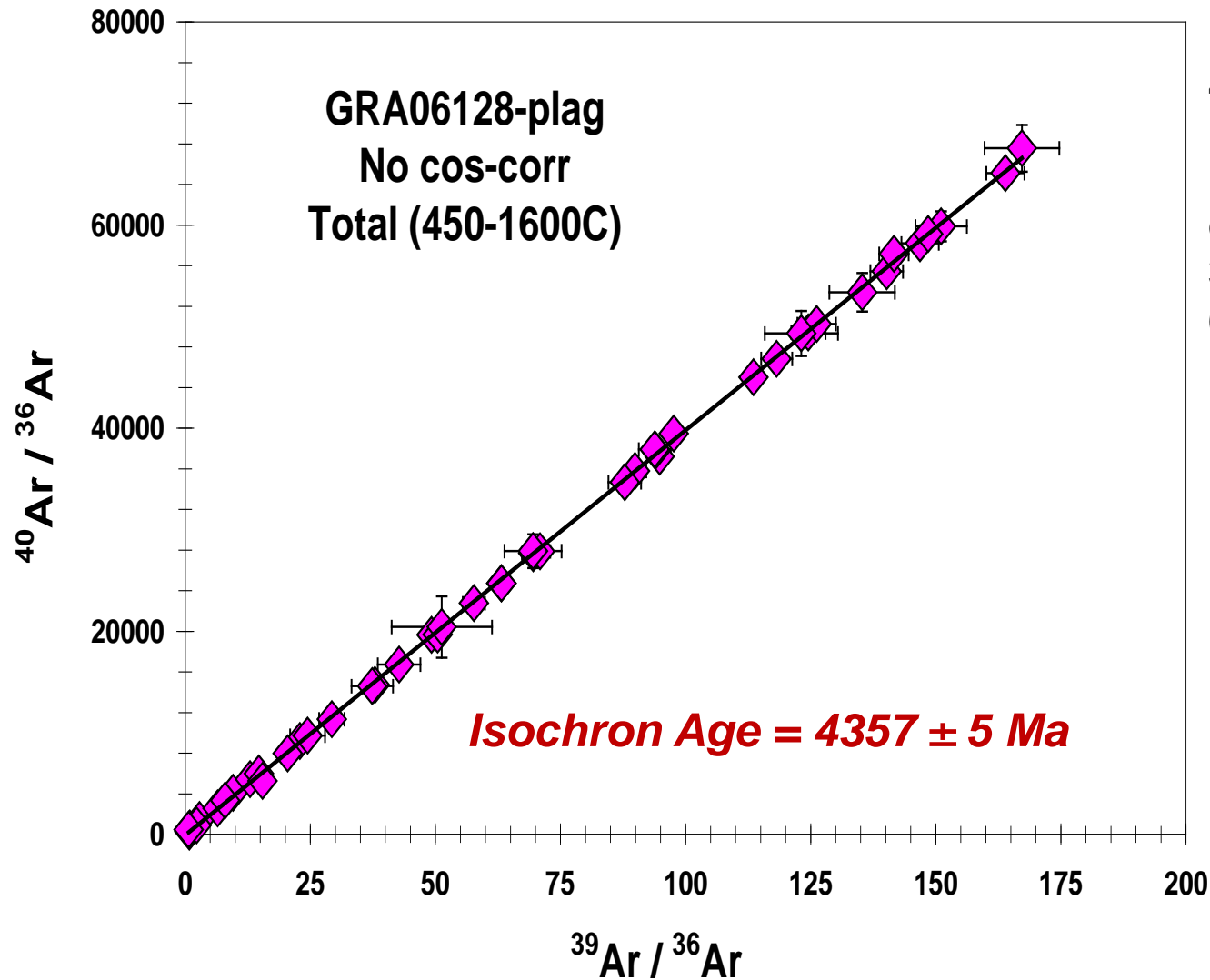


➤ Not ^{40}Ar diffusion loss. Change in K/Ca & ages suggest different K-Ar closure times for different K-bearing phases (e.g., next slide).

Suggests slow cooling.

➤ Ar-Ar age GRA 9 whole rock = 4.460 ± 0.028 Ga (Fernandes et al, 2010). This older age possibly also result of different K-Ar closure times. Difference unlikely to be inter-lab bias.

$^{39}\text{Ar}/^{36}\text{Ar}$ vs. $^{40}\text{Ar}/^{36}\text{Ar}$ for GRA 8



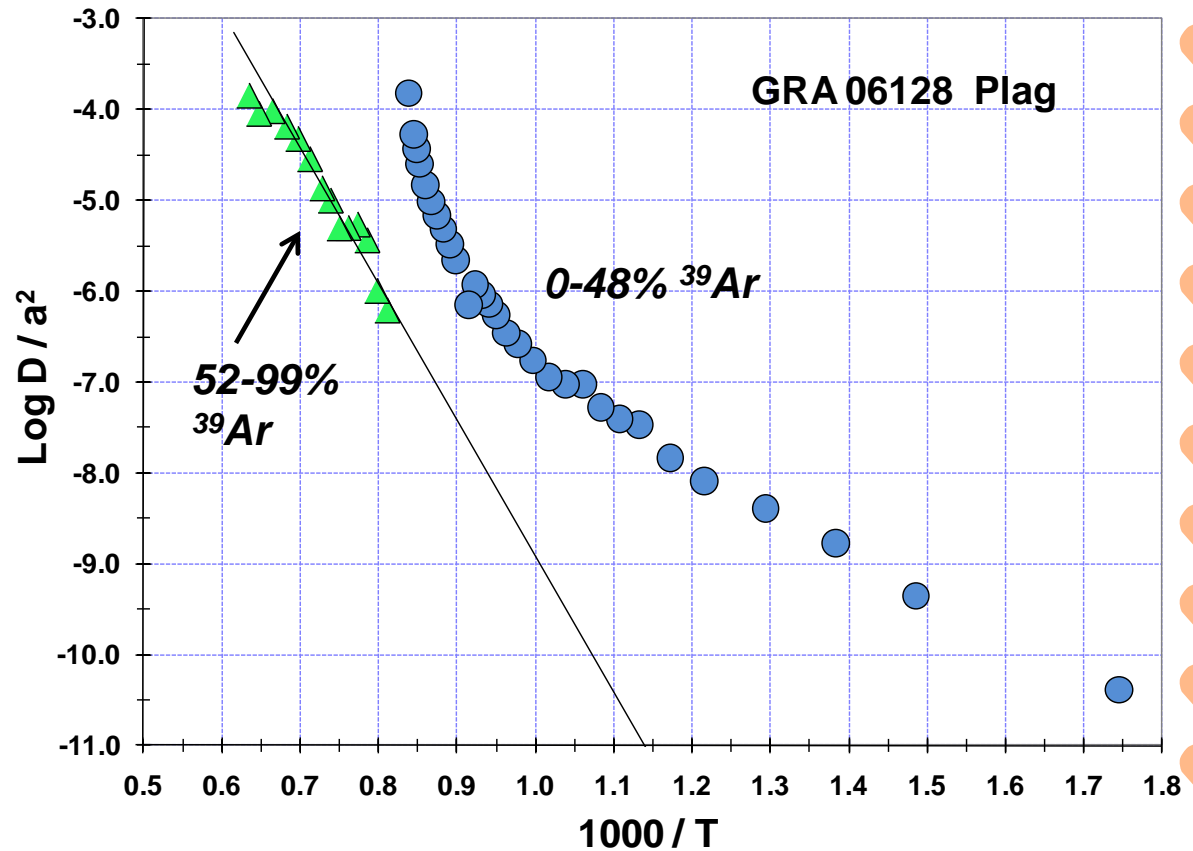
$^{40}\text{Ar}/^{36}\text{Ar}$ intercept near 0, but mixed cosmogenic ^{36}Ar & trapped (air) ^{36}Ar makes imprecise.

Consistent with previous. Indicates no trapped or redistributed ^{40}Ar .

Arrhenius Plot for GRA 8

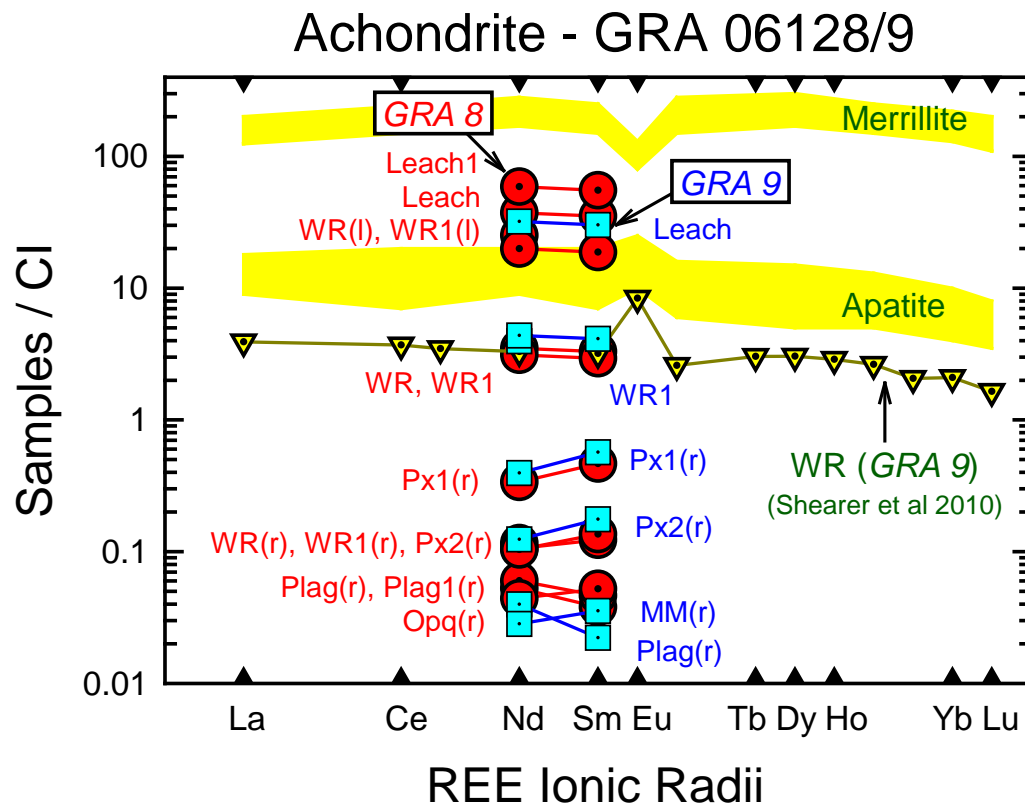
Ar diffusion parameter (D/a^2) for Higher-Temp & Lower-Temp “phases”.
Curved portion indicates complex diffusion even in this constant K/Ca phase.

Plot suggests High-T and Low-T phases have different Ar diffusion characteristics, consistent with different release temperatures. This would imply different K-Ar closure temperatures in a cooling environment.

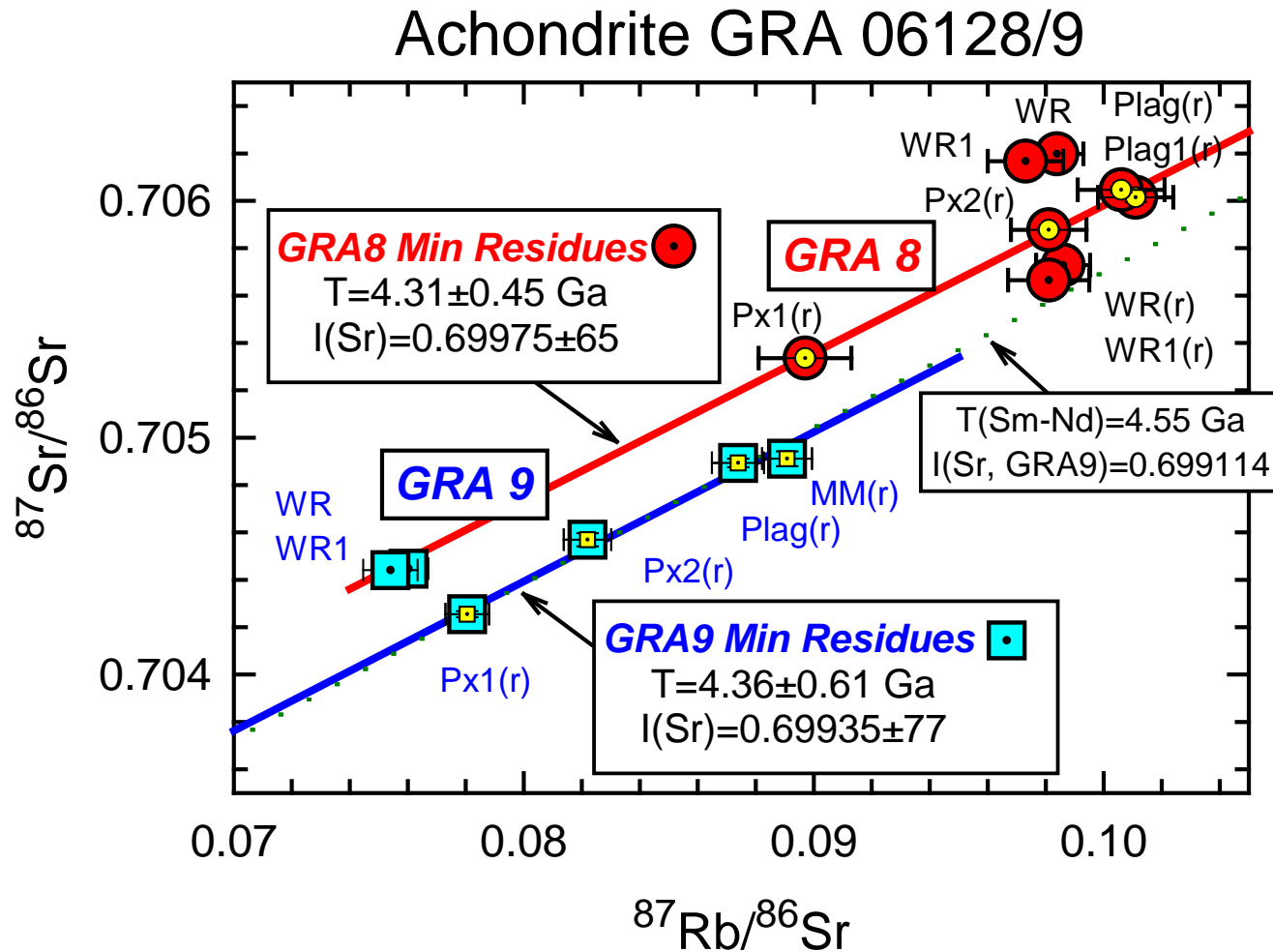


REE for GRA

REE in plag separates are 3-4 orders of magnitude lower than in phosphates. Can be affected by secondary processes that do not affect phosphates or pyroxenes.



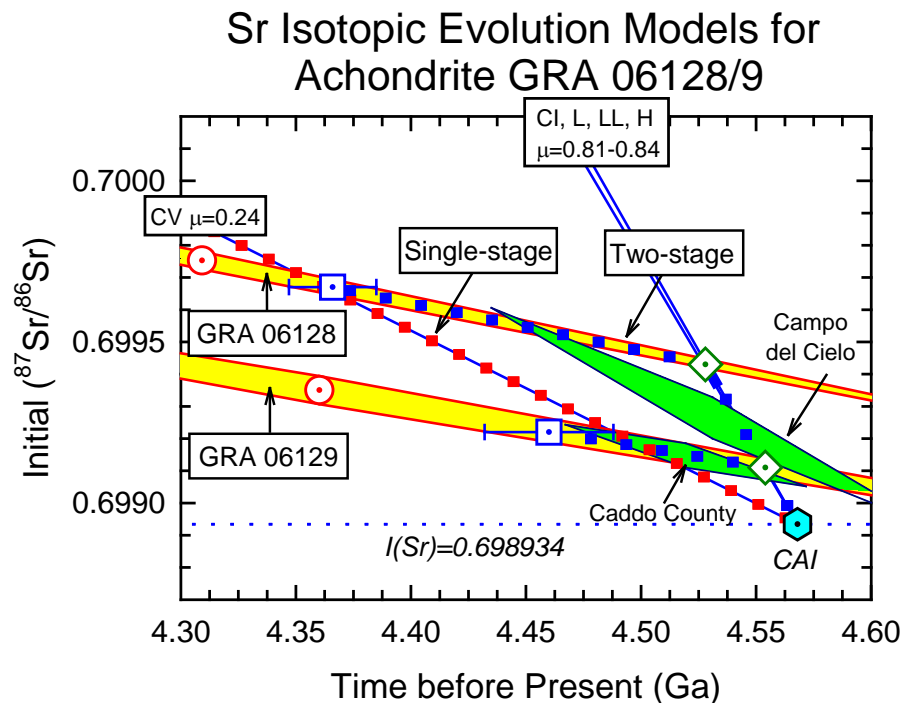
(Rb-Sr) for GRA 8 & 9



$(^{87}\text{Sr}/^{86}\text{Sr})_i$ for GRA 8 & 9

Rb-Sr data in a (Time, I_{Sr}) plot. Ar-Ar ages for GRA 8 and GRA 9 are plotted within the error parallelograms for the Rb-Sr data.

→ Ar-Ar & Rb-Sr data are consistent in (1) GRA 8 & GRA 9 differ, (2) the Ar-Ar ages are close to the nominal ages obtained from the Rb-Sr isochrons.

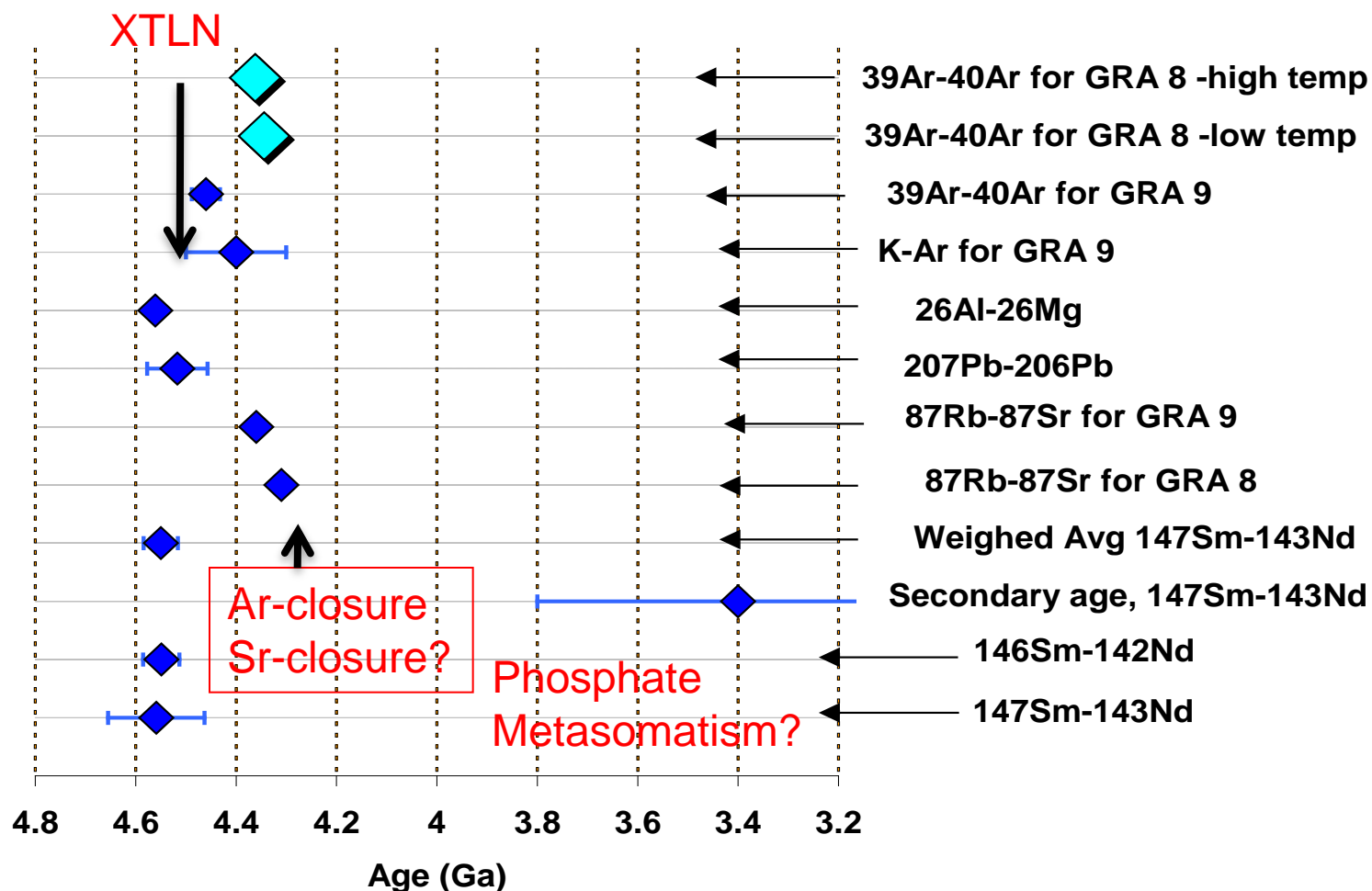


➤ ^{39}Ar - ^{40}Ar ages as crystallization ages require a precursor with low $^{87}\text{Rb}/^{86}\text{Sr} \sim 0.24$ like that in CV chondrites. (single-stage evolution).

➤ ~ 4.56 Ga crystallization ages require slow cooling to maintain open Ar-systems for ~ 150 - 200 Ma. (two-stage evolution).

➤ Two stage evolution allows parent body with typical chondritic $\mu = ^{87}\text{Rb}/^{86}\text{Sr}$ like silicate inclusions in IAB irons.

Age comparison for GRA 8 & 9



39Ar-40Ar for GRA 8 (Park et al, 2010) -high temp, 39Ar-40Ar for GRA 8 (Park et al, 2010) -low temp; 39Ar-40Ar for GRA 9 (Fernandes et al, 2010); K-Ar for GRA 9 (Matsuda et al, 2008); 26Al-26Mg (Shearer et al, 2010); 207Pb-206Pb (Day et al, 2009); 87Rb-87Sr for GRA 9 (Nyquist et al, 2009); 87Rb-87Sr for GRA 8 (Nyquist et al, 2009); Weighed Avg 147Sm-143Nd (Nyquist et al, 2009); Secondary age, 147Sm-143Nd (Nyquist et al, 2008); 146Sm-142Nd (Nyquist et al, 2009); 147Sm-143Nd (Nyquist et al, 2009)

Alternate Scenarios - I

(1) Preferred:

- **Parent body formed ~4.56 Ga ago, GRA rocks crystallized from parent magma**
- **Parent body cooled slowly**
 - **Different mineral hosts closed to Ar diffusion at different times**
 - **4.344- 4.362 Ga (4.357 ± 0.005 Ga) for GRA 8**
 - **4.460 ± 0.028 for GRA 9**
- **Possible metamorphism/metasomatism of rocks ~3.4 Ga ago.**

This scenario requires a large, slowly cooling parent body subject to impact bombardment for ~1 Ga.

Alternate Scenarios - II

(2) Less likely:

- Parent body formed ~4.56 Ga ago
 - Magmatism on the parent body persisted until ~4.3-4.4 Ga
 - 4.460 ± 0.014 for GRA 9
 - 4.344- 4.362 Ga (4.357 ± 0.005 Ga) for GRA 8
 - ✓ Different Ar-closure time for different “phases” characterized by different K/Ca ratios still required.
 - Possible metamorphism/metasomatism of rocks ~3.4 Ga ago.
- This scenario implies late magmatism on the PB, and allows easy interpretation of the Rb-Sr data, but requires ~4.56 Ga ages to have been carried into the rocks via phosphates introduced via open system reactions with external melts or fluids.

Conclusions

- **Either scenario requires a large parent body.**
- **Some combination of the proposed scenarios may be possible, but requires observations independent of the isotopic systematics.**
 - **For example, reaction of acidic fluids with pre-existing phosphates in the rocks could lead to disturbance of the Sm-Nd system in low-REE plagioclase.**
 - **Leads to a modified “Scenario Ib”**
 - **Perhaps most likely**